Dynamic Radiative Surface Properties with Origami-Inspired Topography

THERMAL & FLUIDS ANALYSIS WORKSHOP

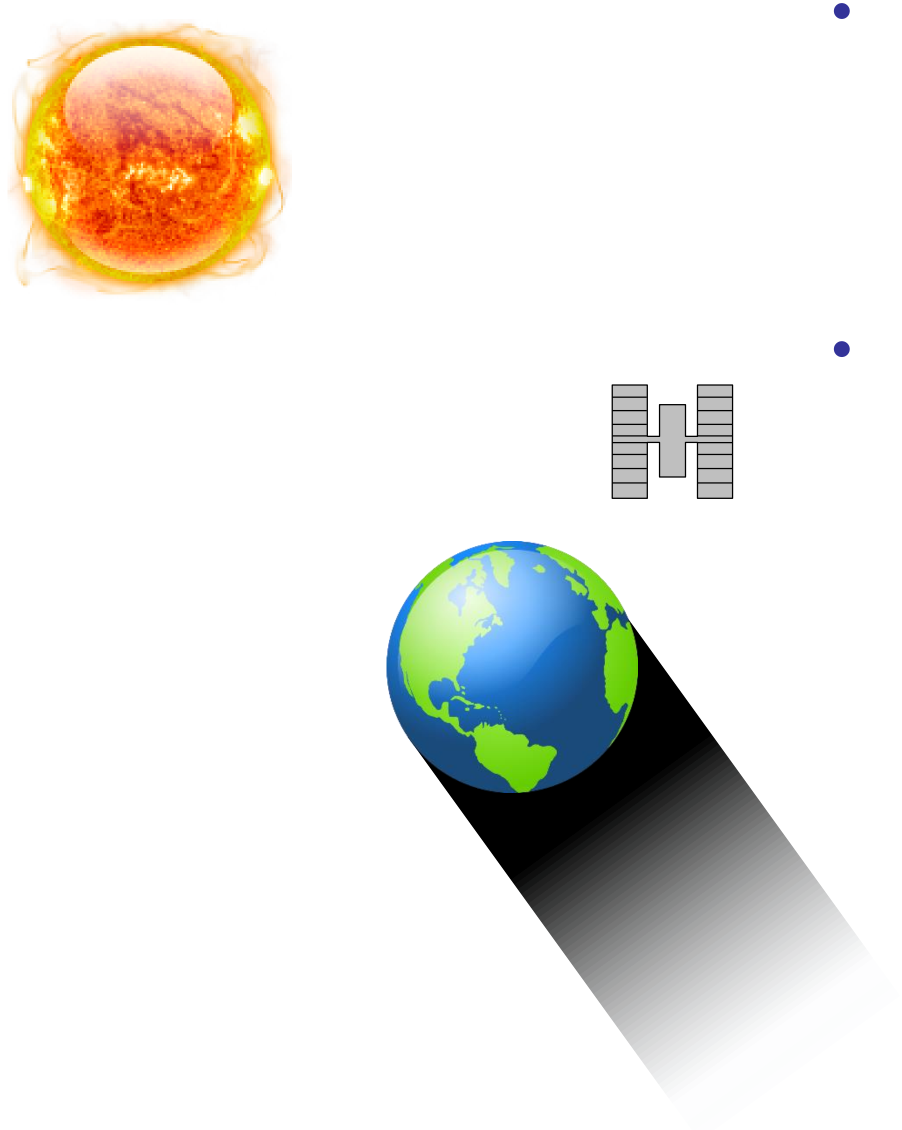
GSFC · 2015

Rydge B. Mulford
Mitchell J. Blanc
Dr. Matthew R. Jones
Dr. Brian D. Iverson

BRIGHAM YOUNG UNIVERSITY · PROVO, UTAH · FOUNDED 1875 BYU

flux lab

Heating Conditions in Orbit



- Large variations in thermal environment but static radiative surface properties

- Current Solutions
  - Multi-Layer Insulation
  - Heaters
  - Spectrally-selective surfaces
  - Louvers

Variable Emissivity Devices

- Surfaces capable of changing emissivity and absorptivity in real time

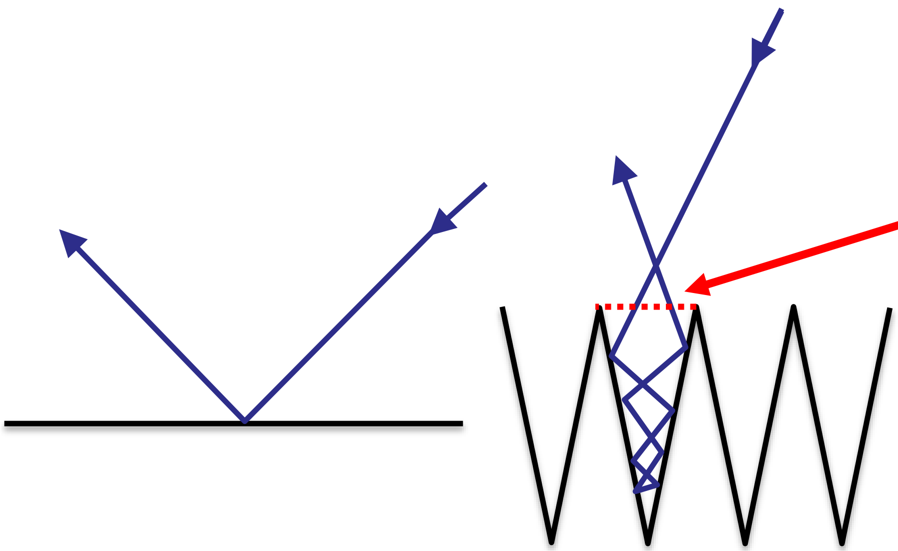
- Current variable emissivity devices rely on various mechanisms to vary emissivity
  - Modification of surface chemistry
  - Modification of heat transfer mode

What about geometry modifications ?

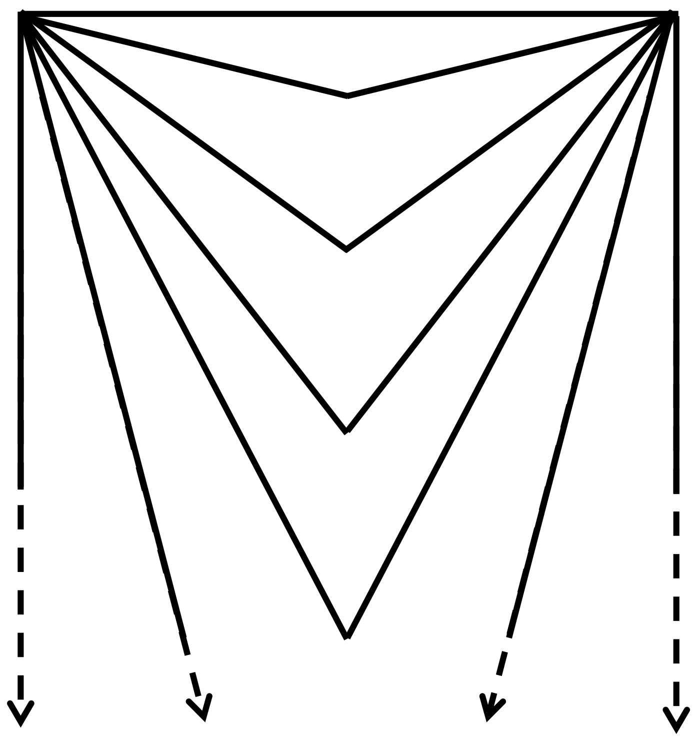
The Cavity Effect

- Reflections inside a cavity create an increase in apparent surface properties

$$\varepsilon_a = \frac{E_{cavity}}{E_{black}}$$



Apparent Surface Behavior



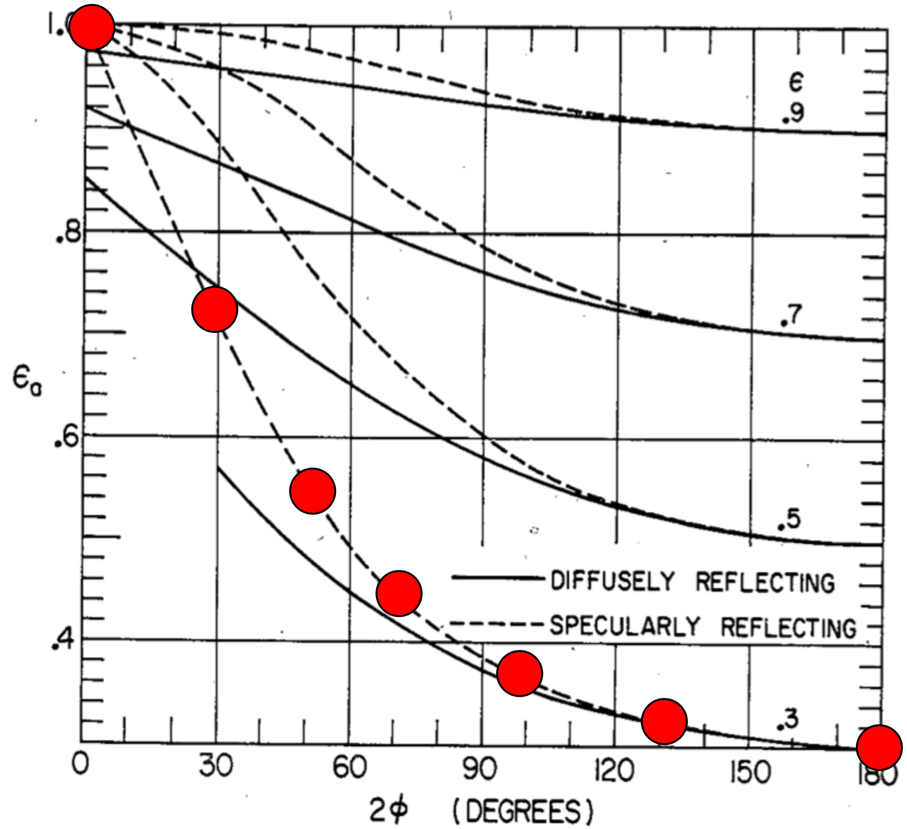


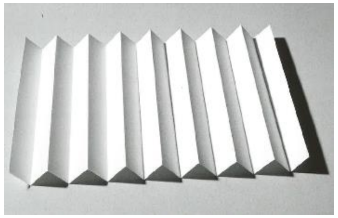
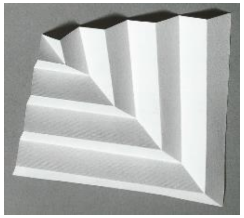
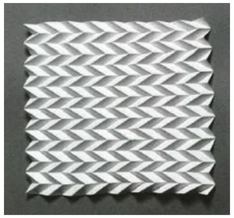
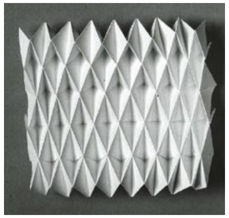
Fig. 6-6 Apparent emittance results for diffusely and specularly reflecting V-groove cavities.

Sparrow and Cess, Radiation Heat Transfer, 1978

Real World Implementation?

Origami and the Cavity Effect

- 1D actuation manipulates cavity angle
- Simple to advanced fold patterns exist
- Models exist to describe accordion fold

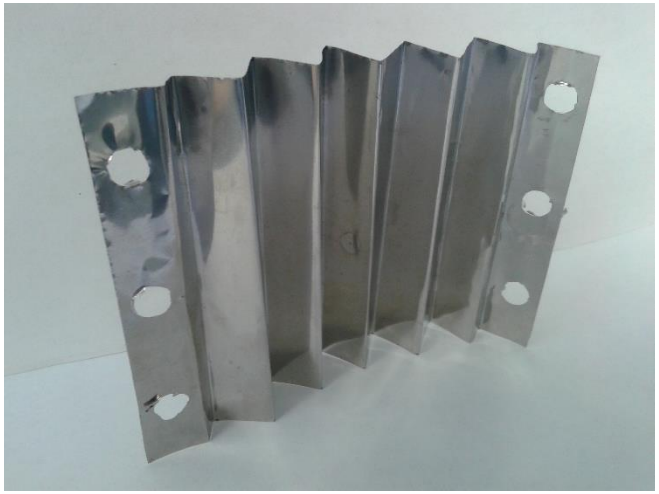
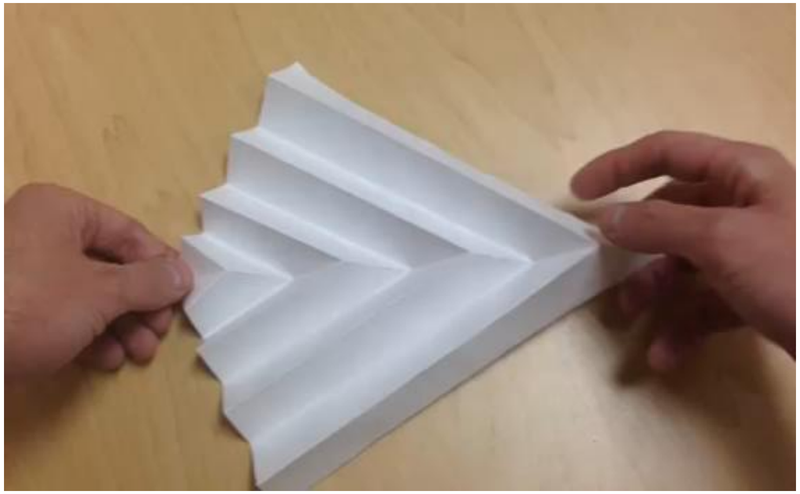



Image Credit: Jackson. Folding Techniques for Designers

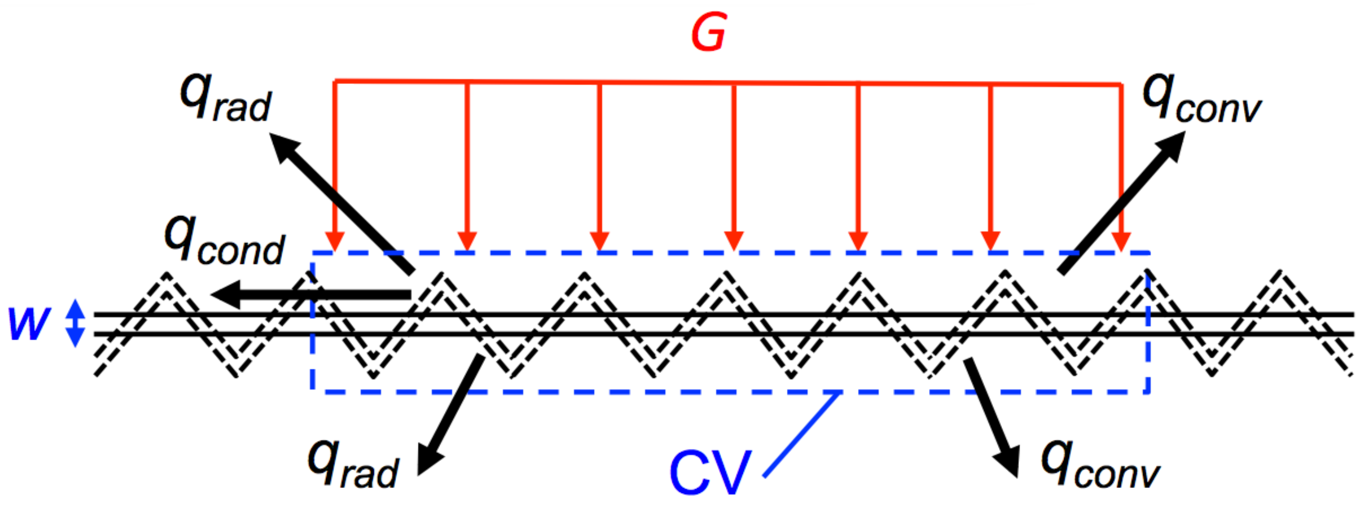
Purpose of this Work

- Determine the following as a function of geometry:
  - Apparent absorptivity
  - Apparent emissivity
  - Rate of net radiative heat exchange with the surroundings

- Methods must apply to any origami fold pattern.

Apparent Absorptivity

Apparent Absorptivity Energy Balance



- Energy Balance

$$mC_P \frac{dT}{dt} = \alpha_a G_B A_B - (q_{conv} + q_{rad} + q_{cond})$$

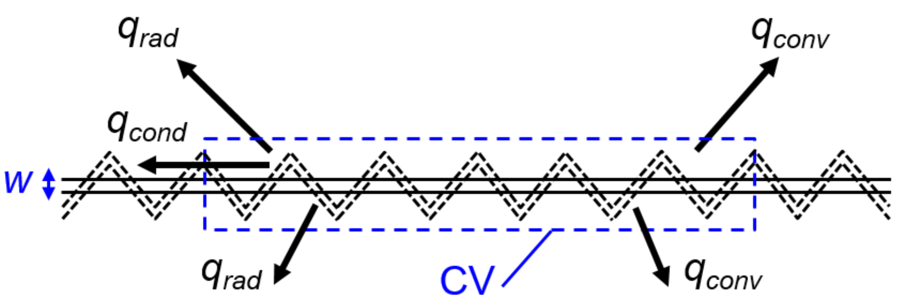
- Governing Equation
  - Non-dimensionalized
  - Overall heat transfer coefficient

$$\frac{d\theta}{dt} + \underbrace{\sin\left(\frac{\phi}{2}\right)\left[\frac{U(t)}{\rho w C_P}\right]}_{\text{Heat Loss Term}} \theta = \underbrace{\sin\left(\frac{\phi}{2}\right)\frac{\alpha_a G_B}{\rho w C_P}}_{\text{Heat Addition Term}}$$

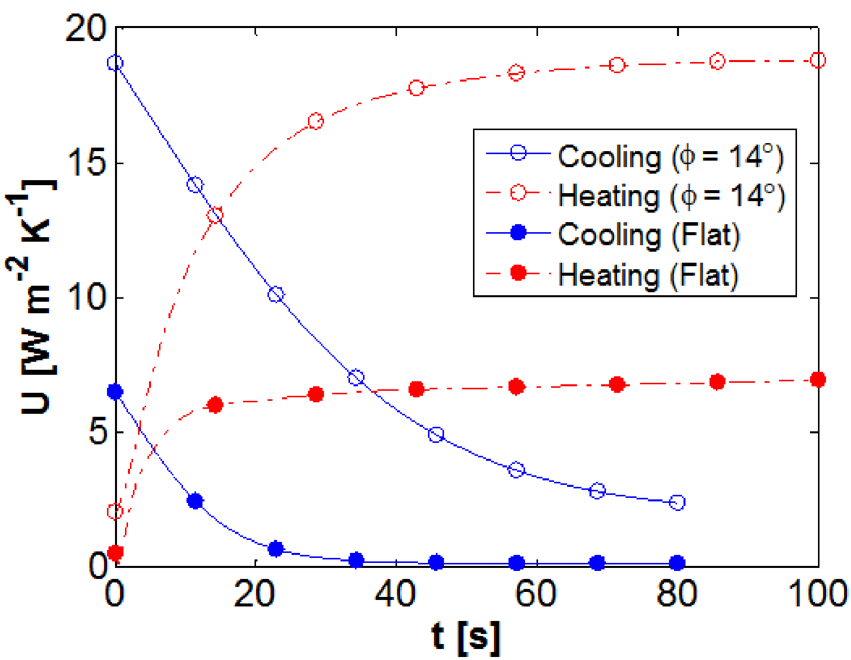
- U(t) characterizes conductive, convective and radiative heat losses

$$\frac{d\theta}{dt} + \sin\left(\frac{\phi}{2}\right)\left[\frac{U(t)}{\rho w C_P}\right]\theta = \cancel{\sin\left(\frac{\phi}{2}\right)\frac{\alpha_a G_B}{\rho w C_P}}$$

$$U(t) = 2h + 2h_r + \frac{Sk}{A_B}$$



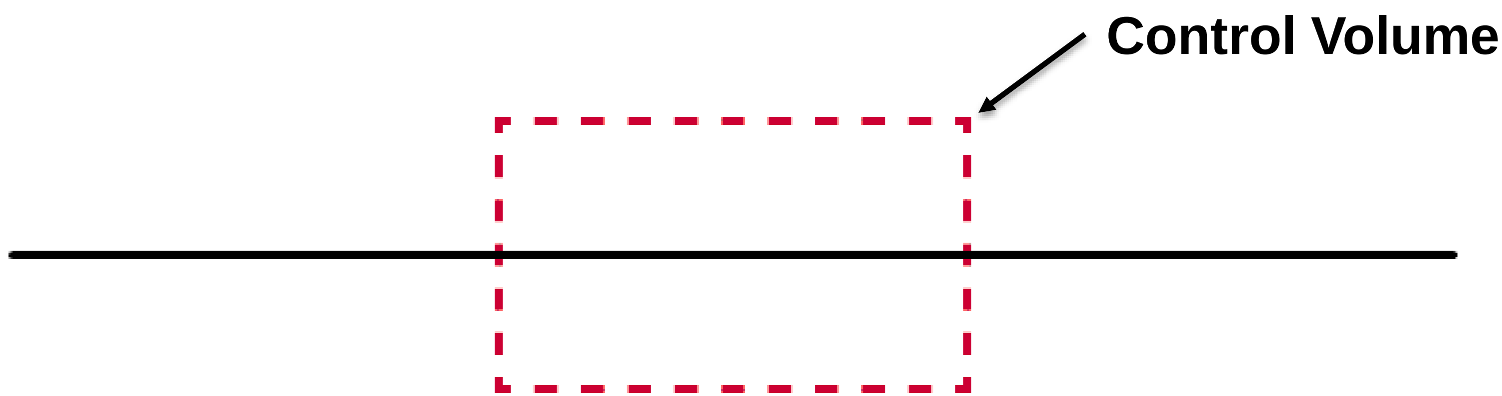
$$U(t) = \left[\frac{-\,r\,wC_P}{\sin\left(f/2\right)}\right]\frac{1}{q}\frac{dq}{dt}$$



Mass Compensation

- Volume Ratio
  - Accounts for increasing mass in control volume as sample is actuated
  - Different origami folds would have different ratios

$$\frac{V_B}{V_{folded}} = \frac{A_B}{A_{folded}} = \boxed{\frac{1}{\sin\left(\phi/2\right)}}$$



Inverse Model Solutions

$$\frac{d\theta}{dt}+\sin\left(\frac{\phi}{2}\right)\left[\frac{U(t)}{\rho w C_P}\right]\theta=\sin\left(\frac{\phi}{2}\right)\frac{\alpha_a G_B}{\rho w C_P}$$

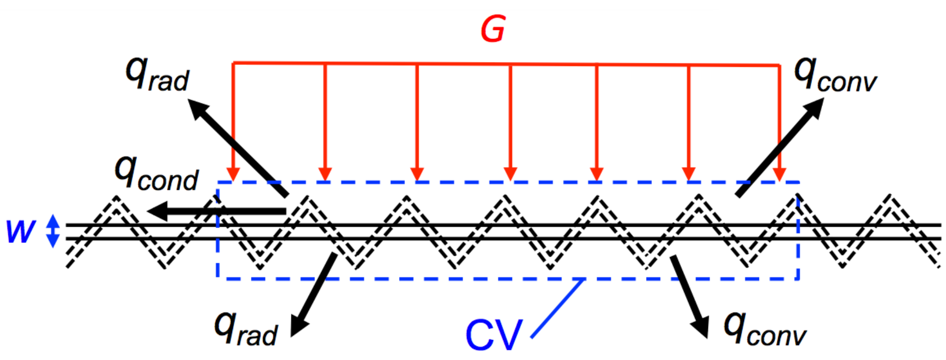
- Direct Method
  - The governing equation was rearranged
- Integrating Factor Method
  - An integrating factor was used to solve the differential equation

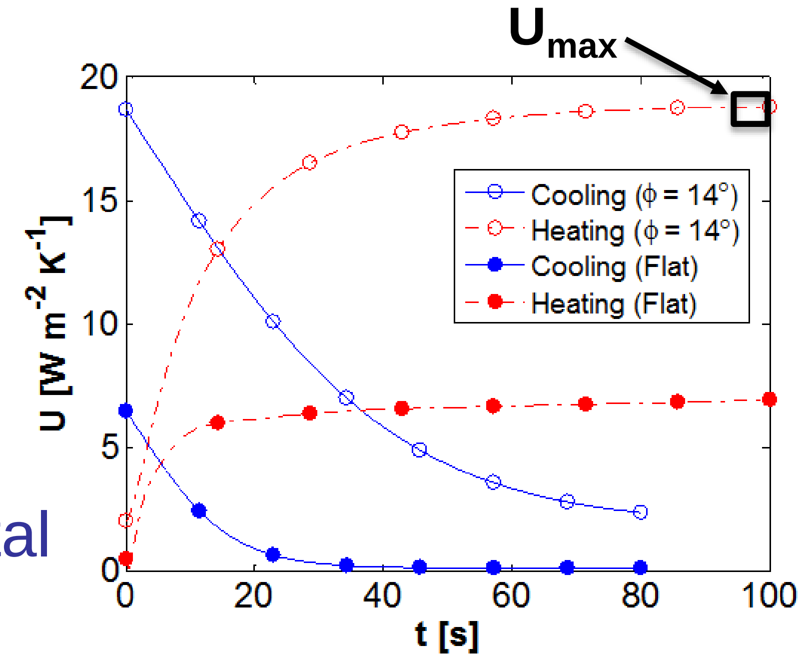
Integrating Factor Method	Direct Method
$\alpha_a=\dfrac{\dfrac{U_{\max}}{G_B}(\theta-\theta_0)}{1-e^{\frac{-U_{\max}t}{\rho w C_P}\sin\left(\frac{\phi}{2}\right)}}$	$\alpha_a=\dfrac{\rho w C_P}{G_B\sin\left(\dfrac{\phi}{2}\right)}\left[\dfrac{d\theta}{dt}+\sin\left(\dfrac{\phi}{2}\right)\dfrac{U(\Delta T(t))}{\rho w C_P}\theta\right]$

Steady State Model

- The steady state energy balance gives absorptivity as a function of G, θ_{SS} and U_{max}

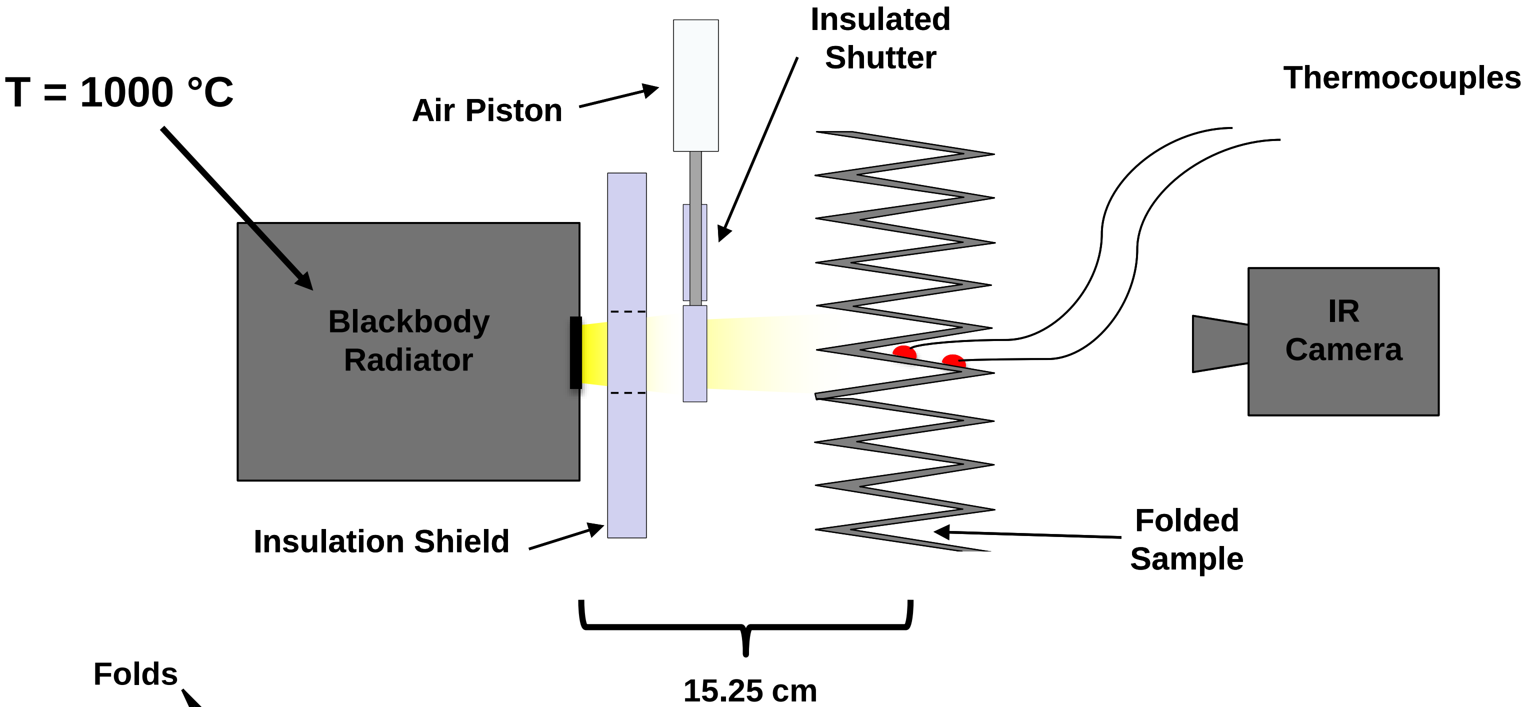
$$\cancel{\frac{d\theta}{dt}} + \sin\left(\frac{\phi}{2}\right)\left[\frac{U(t)}{\rho w C_P}\right]\theta = \sin\left(\frac{\phi}{2}\right)\frac{\alpha_a G_B}{\rho w C_P} \Rightarrow \boxed{\alpha_a = \frac{U_{max}\theta_{SS}}{G_B}}$$

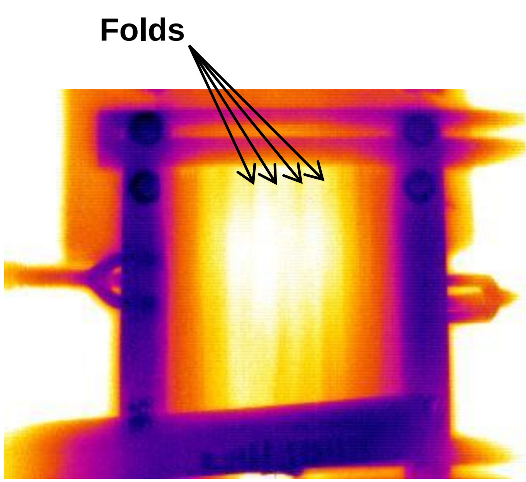


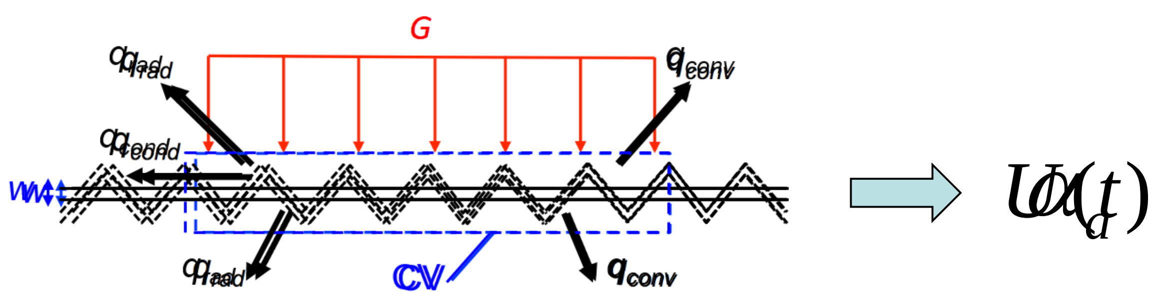


- All solutions require experimental temperature measurements

Experimental Setup

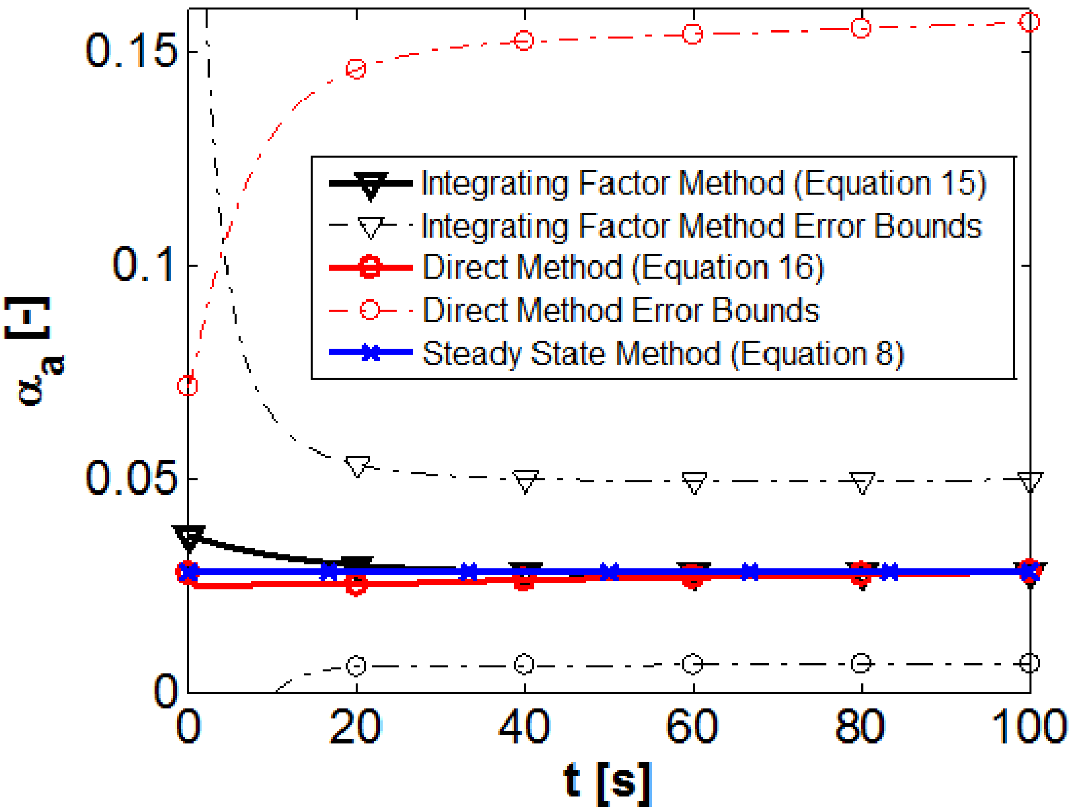






Experimental Results (Flat Sample)

- Absorptivity results with respect to time for three methods



Flat Sample Validation

- Flat sample was measured with a reflectometer
  - Independent verification of inverse model results

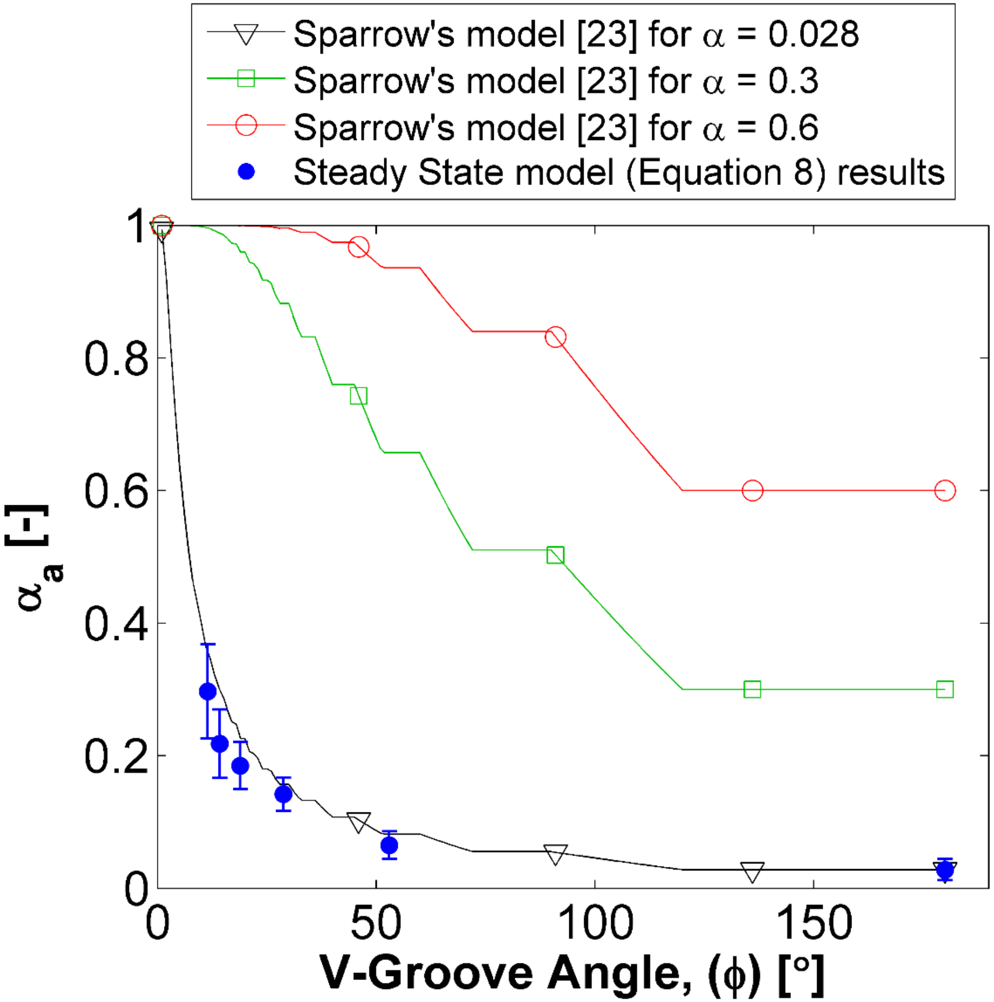
Test #	Spectral Range (Micrometers)					
	1.5 – 2.0	2.0 – 3.5	3.0 – 4.0	4.0 – 5.0	5.0 – 10.5	10.5 – 21.0
	Spectral Reflectivity					
1	0.965	0.969	0.966	0.977	0.982	1.005
2	0.967	0.972	0.971	0.973	0.983	1.01
3	0.965	0.969	0.973	0.977	0.98	0.986

Emissometer Absorptivity	**0.028**
Steady State Model Absorptivity	**0.028**

$$\alpha = \sum_{i=1}^{6} F_i \left(1 - \rho_{r,i}\right)$$

Folded Sample Validation

- Experimental and theoretical results show that a surface with any intrinsic absorptivity can achieve $\alpha_a = 1$



Sparrow's Equations

$$\alpha_a = 1 - (1 - \alpha X')(1-\alpha)^{n-1}$$

where:

$$X' = \frac{\sin\left[\left(n - \frac{1}{2}\right)\phi\right]}{\sin\left(\frac{\phi}{2}\right)}$$

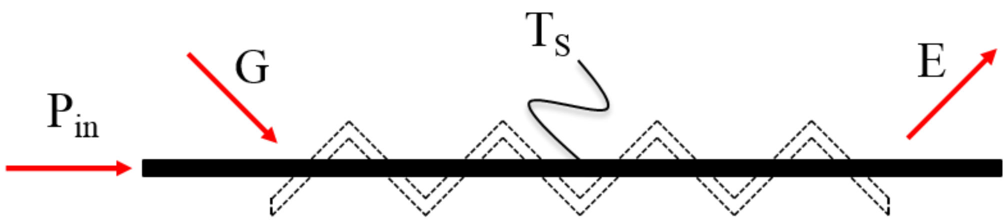
$$n = \left\lfloor \frac{180}{\phi} + \frac{1}{2} \right\rfloor$$

(1962, IJHMT, Sparrow)

Apparent Emissivity

Theoretical Apparent Emissivity

- A new experimental approach is necessary to find ϵ_a
- We will consider an origami surface subjected to uniform electrical heating (P_{in})

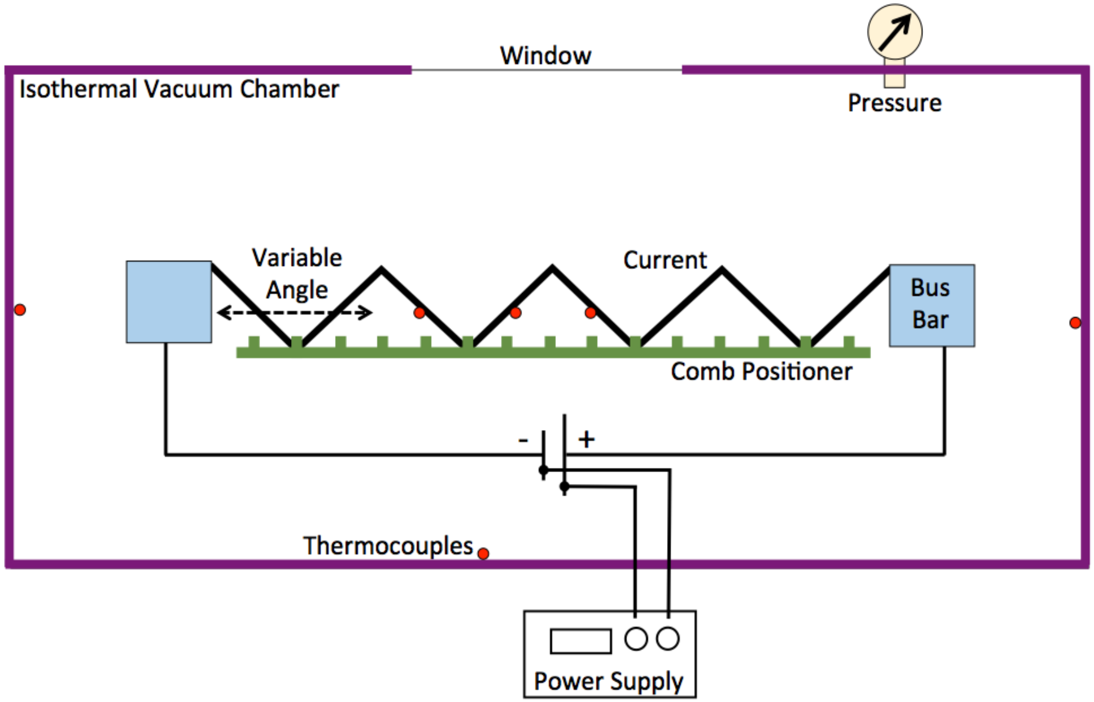


$$P_{in} = A_{projected}(\phi)E(\phi) - A_{projected}(\phi)\alpha_a(\phi)G \quad \Longrightarrow \quad A_{projected} = A_{initial}\sin\left(\frac{\phi}{2}\right)$$

$$\boxed{\varepsilon_a = \frac{P_{in}}{A_i \sin\left(\frac{\phi}{2}\right)\sigma T_s^4} + \alpha_a \frac{T_{surr}^4}{T_s^4}}$$

Apparent Emissivity Experimental Setup

- Experiments were performed in a vacuum chamber evacuated to a vacuum of 0.015 Torr
- Surface was heated using Joule heating
- A correction was made for the heating of the bus bars and losses in the electrical wires



Apparent Emissivity Results

- Experimental results are not yet complete

- Modest's equation will be used to benchmark apparent emissivity results (diffuse emitter, specular reflector):

$$\varepsilon_a = \frac{\varepsilon}{\sin\phi}\left[1-\varepsilon\sum_{k=1}^{n}\rho^{k-1}\left(1-\sin\left(k\phi\right)\right)\right], \quad n<\frac{\pi}{2\phi}$$

From Modest, 2nd ed.

- Modest's equation can be used for apparent emissivity when considering net radiative heat exchange

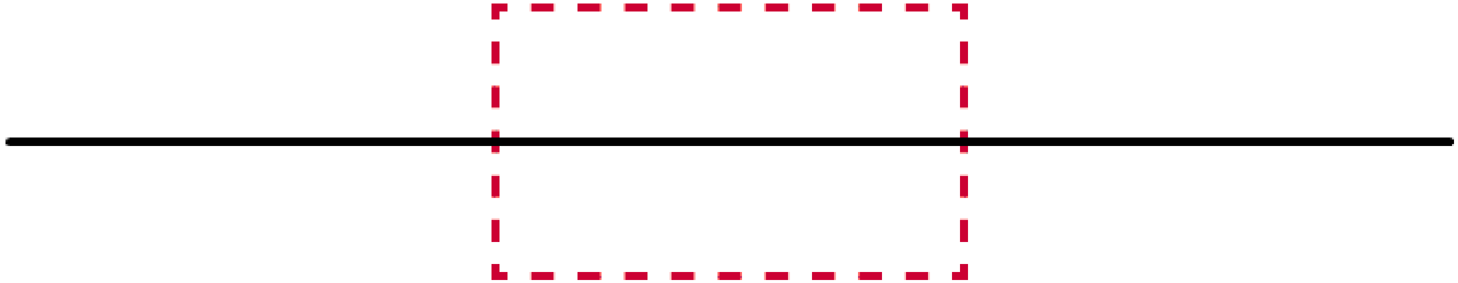
Net Radiative Heat Exchange

(Diffuse emitter, specular reflector, collimated/diffuse irradiation)

Variable Surface Area Considerations

- As the surface is compressed:
  - The apparent emissivity/absorptivity increase
  - The emitting area decreases

- What will be the effect on total radiative heat exchange with the surroundings?



Theoretical Heat Rate

- Same energy balance and governing equation as apparent emissivity analysis

- For a diffusely emitting, specularly reflecting surface

Collimated Irradiation

$\alpha_a =$ Sparrow's Equations

$$q_{net,radiation} = \sigma A_i \sin\left(\frac{\phi}{2}\right)\left(\varepsilon_a T_s^4 - \alpha_a T_{surr}^4\right)$$

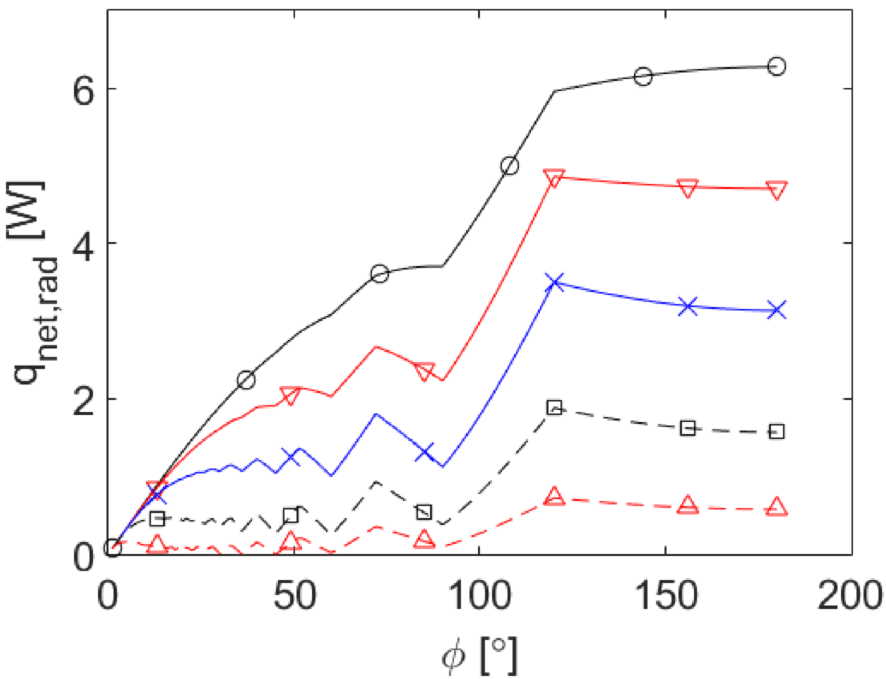
Diffuse Irradiation

$$\alpha_a = \varepsilon_a$$

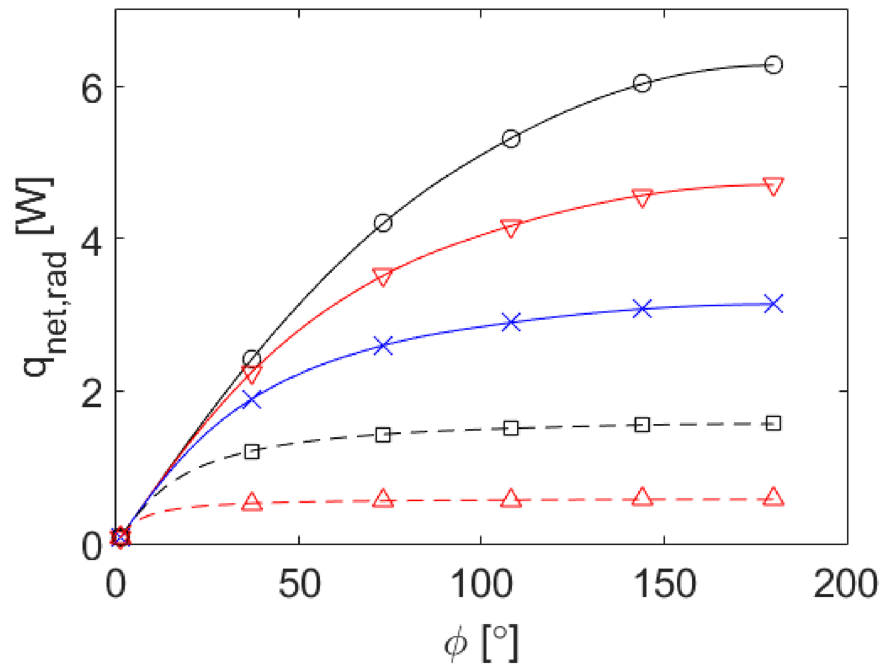
$$q_{net,radiation} = \varepsilon_a \sigma A_i \sin\left(\frac{\phi}{2}\right)\left(T_s^4 - T_{surr}^4\right)$$

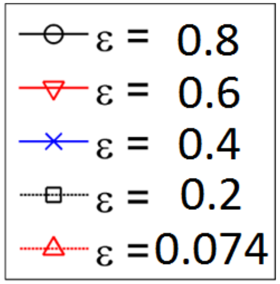
Theoretical Heat Rate Results

Collimated Irradiation



Diffuse Irradiation



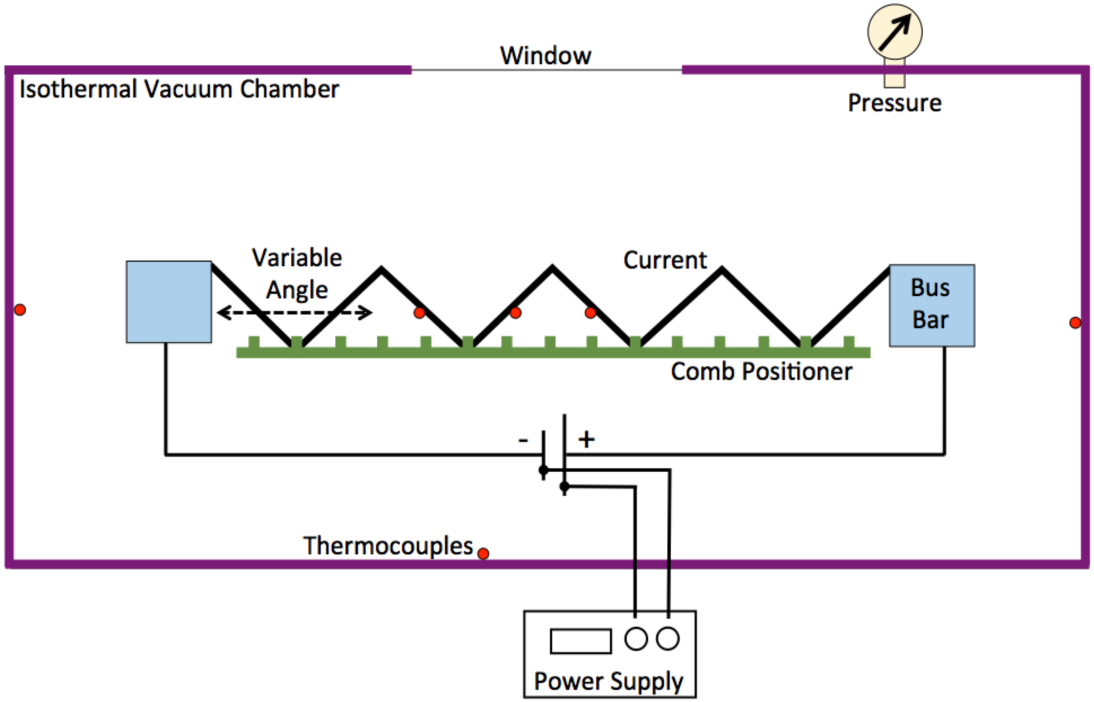


- Heat rate *decreases* with decreasing fold angle
- Collimated irradiation doesn’t decrease monotonically

Heat Rate Experimental Setup

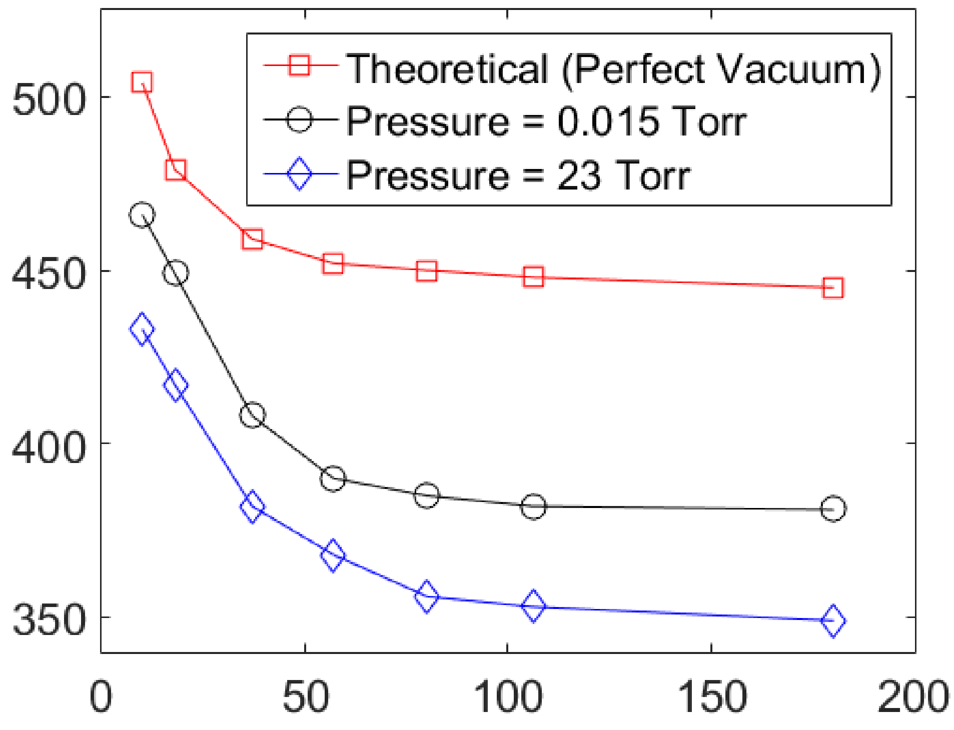
- Same setup as used in the apparent emissivity test

- Temperature data collected at three power levels and interpolated to find power as a function of fold angle at a constant temperature (T = 325 K)



Experimental Results – Temperature

- Guys and Ellis found a pressure of 10^{-5} Torr is necessary to eliminate conductive losses
- Our setup is limited to 0.015 Torr



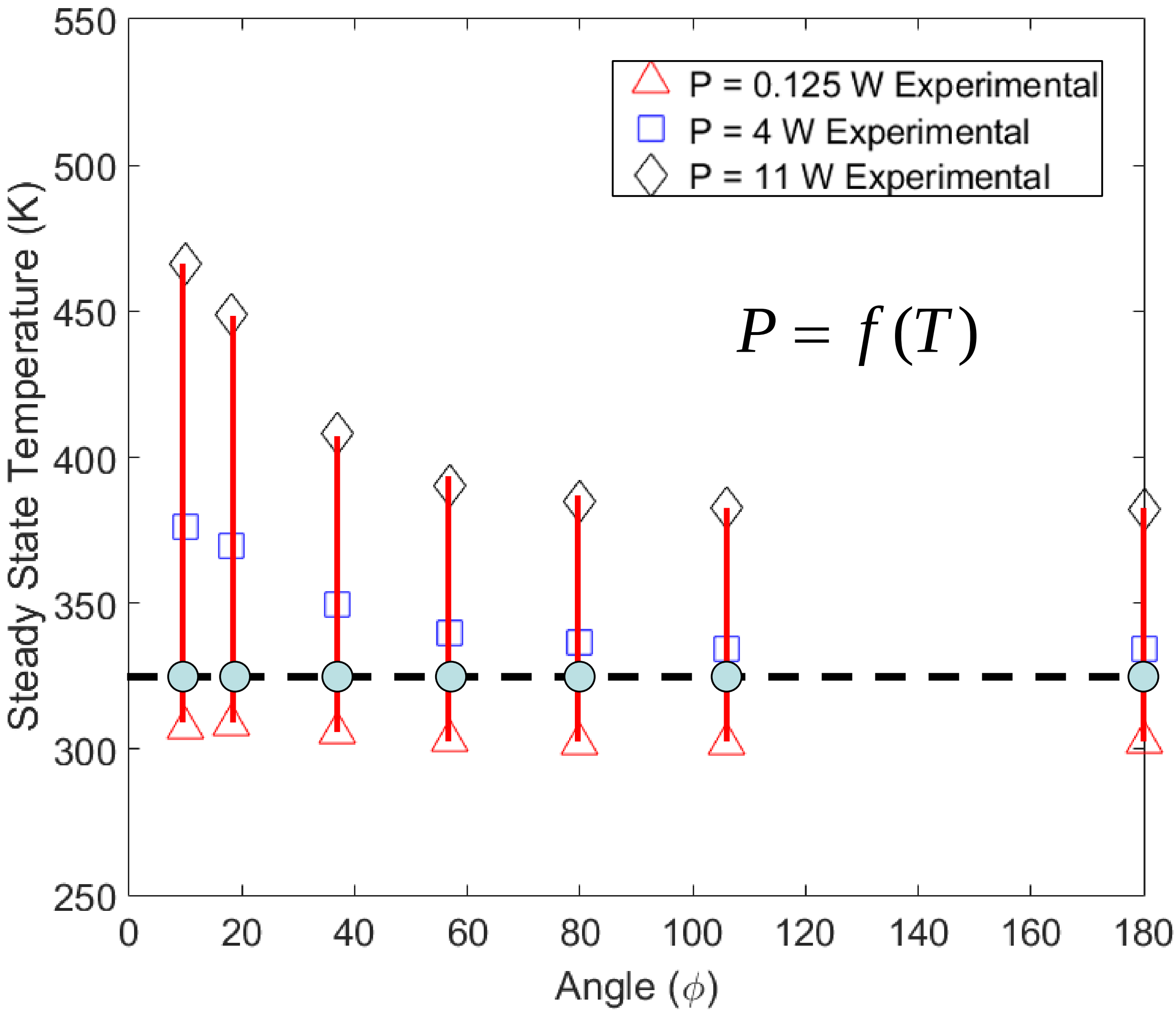
(1963, NASA, Guys and Ellis)

Experimental Results – Power Derivation

1) Defined a set temperature

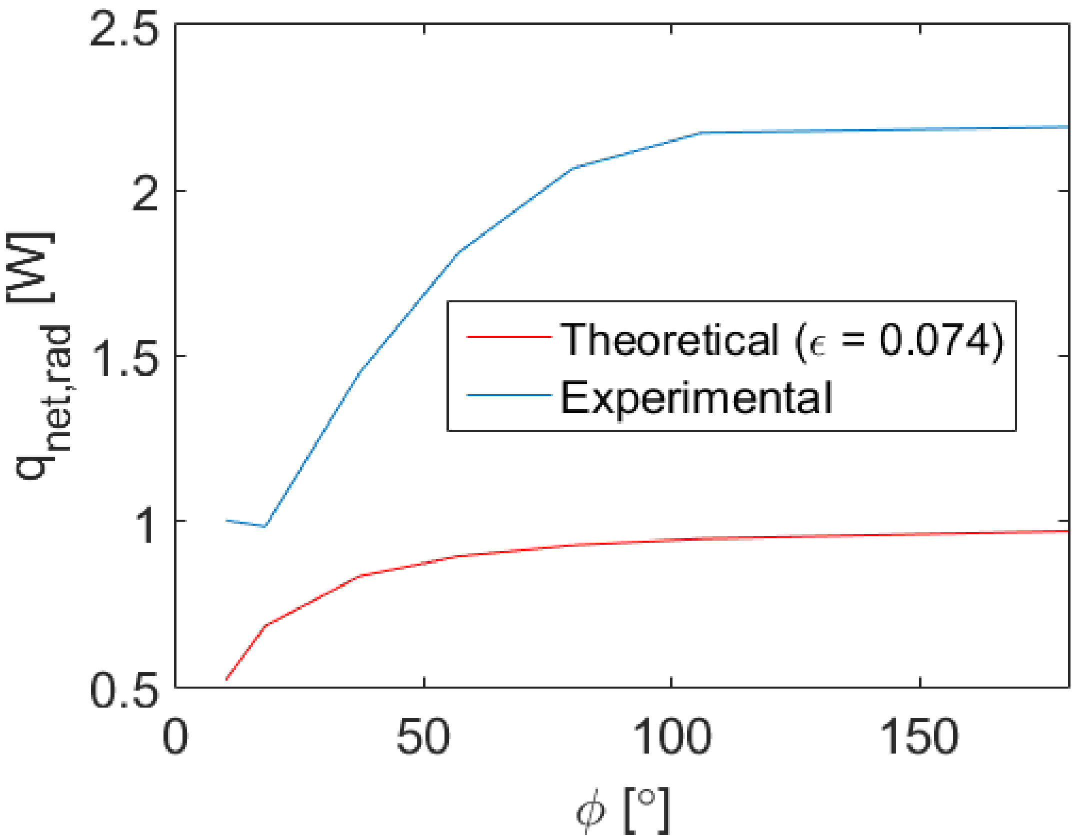
2) Curve fit temperature vs. power data

3) Evaluated T = 325 K at each angle to find power as a function of angle



Experimental Results – Power

- Net radiative heat exchange for an origami surface as a function of cavity angle for a constant T = 325 K
- Heat rate decreases as cavity angle decreases



Conclusions

- Experimental facilities have been developed to find radiative properties as a function of cavity angle
- These methods may be used to characterize origami folds that cannot be modeled theoretically
- The heat rate decreases as the cavity angle is decreased because the angle term approaches zero
- Origami surfaces are capable of varying their apparent absorptivity and emissivity from very low (0.028) to unity

Future Work

- Surfaces that maintain a constant projected surface area should be explored.
- Investigate 2D and 3D origami surfaces
- Characterize spectral properties using FTIR
- Maintain the temperature of an origami surface through actuation under varying irradiation conditions